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Airframe Structural Materials for Drone Applications

Donald F. Adams

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10. ABSTRACT

A comparison of performance, weight, and cost characteristics of a wide range of structural materials for aircraft. ~~The aircraft speeds considered range from very low subsonic to high supersonic.~~ Materials ranging from polyester-impregnated paper and wood to titanium and the high-performance reinforced composites are compared with conventional aluminum alloys for subsonic vehicles. At high supersonic speeds, aerodynamic heating dictates use of high-temperature materials such as coated columbium, molybdenum, and TD nickel alloys. Fuselage, wing, tail, and engine nacelle components are individually considered for 5 representative subsonic and 3 supersonic configurations; 9 different material combinations are evaluated for the subsonic and 8 for the supersonic vehicles. Subsonic airframe total weights range from 36% less than conventional aluminum alloy to 34% more. The supersonic airframes weigh 25% less to 160% more than selected base cases. Cost tradeoffs are also considered.

11. KEY WORDS

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PREFACE

This investigation is part of a larger project sponsored by the Advanced Research Projects Agency on costs and performances of military drone vehicles. The work reported here on structural materials is unclassified and has a much broader application; therefore, it is also being published separately to make it readily available.

SUMMARY

A wide variety of materials have been included in the present study, corresponding to the wide range of vehicle speeds being considered. These materials are divided into two groups; those primarily applicable to subsonic cruise speed vehicles, and those required for supersonic flight conditions.

For subsonic airframe structures, candidate materials considered range from polyester-impregnated paper and wood to titanium and the high-performance, filament-reinforced composites. At high supersonic speeds (speeds up to Mach 5.0 are considered), aerodynamic heating effects dictate the consideration of high temperature materials such as coated columbium, molybdenum, and TD nickel alloys.

The airframes of five representative subsonic cruise vehicle configurations and three supersonic vehicles are analyzed in detail. Fuselage, wing, tail, and engine nacelle structural components are individually considered. Nine different material combinations are evaluated for the subsonic vehicle components, and eight for the supersonic vehicle components (six of which are different than for the subsonic applications).

For the subsonic vehicles, airframe total weights ranging from a decrease of 36 percent to an increase of as much as 34 percent compared to a conventional aluminum alloy structure are indicated. Material combinations resulting in increased weights may be of interest for certain applications if the associated material and fabrication costs are significantly lower. Cost factors are therefore also discussed.

For the supersonic vehicles, a different base-case material is assumed for each of the three configurations considered (representing Mach numbers of 2.3, 3.0, and 5.0, respectively). On these bases, weight variations ranging from 25 percent less to 160 percent more are indicated. Some of the material combinations result in increases in both cost and weight for certain configurations, however, indicating their limited practical utility for such applications.

The performance, weight, and cost data contained in this report will be directly applicable to other drone, telecraft, aircraft, and spacecraft structural material selection studies as well.

TABLES

I. INTRODUCTION

The flight profiles considered in this study include a wide range of very low subsonic and high supersonic cruise speeds. Thus, a large number of materials should be considered for the airframe structure. The most promising of these are discussed in detail in this report. Cost and fabrication characteristics are examined, as well as structural properties, which are representative of those currently available or likely to be introduced in the next several years.

The primary emphasis is on potential airframe structural-weight savings that can be achieved by substituting various other materials for those most commonly being used at the present time. These weight savings can be translated into increased drone performance in the sense of increased range, endurance, or payload. Consideration has also been given, however, to the use of various materials to achieve reduced airframe cost or increased performance reliability.

The mission flight profiles considered include no high maneuver requirements. In addition, where air launch and recovery are employed, the maximum launch/recovery loading is limited to about 3 g, and no landing gear and associated heavy airframe attachment structure to transmit landing impact loads are required. These flight conditions are not very taxing with respect to the airframe. Hence the total weight of the airframe structure, expressed as a fraction of the gross takeoff weight of the drone vehicle, may be much lower than that for manned aircraft or for highly maneuverable target drones. For example, the structural weight fractions (defined as the ratio of the total weight of the airframe--fuselage, wings, tail, and engine nacelle--to the gross takeoff weight of the vehicle) of the drones in this study range from approximately 0.11 to 0.29; typical structural weight fractions for manned aircraft range from 0.25 to 0.35. Obviously, the higher the structural weight fraction, i.e., the heavier the structure is relative to the remainder of the vehicle system, the greater the potential for weight reduction by materials substitution.

For several of the drones to be analyzed in detail, the weight of the payload is greater than that of the entire airframe. Hence, one's first impression might well be that a small reduction in total airframe weight is of little significance. However, as the mission flight profile begins to approach the limits of the performance capability for a specific drone, e.g., very high cruise altitudes or speeds, and under severe launch and/or recovery conditions, the performance efficiency of the airframe structure becomes much more important.

II. CANDIDATE MATERIALS

Fifteen different materials, including the aluminum alloys currently in general use, have been considered for subsonic drones. These materials are listed in Table 1. Additional materials, having better elevated-temperature properties, will be introduced later in the discussion of cases where aerodynamic heating effects associated with supersonic flight become a dominant factor. Some of the candidate materials have particularly high specific strength characteristics (strength divided by density); these materials are most advantageously used in strength-critical components of the structure, e.g., fuselage frames and secondary structure.* Other materials have excellent specific stiffness properties (stiffness divided by density) and are superior in stiffness-critical components, e.g., wing and tail assemblies, particularly in the form of highly stressed skins. Thus, the potential weight savings of a given material, relative to aluminum, depend upon the particular application. Some materials, e.g., unreinforced ABS plastics,** may actually result in a weight penalty, as indicated by the negative numbers in parentheses in Table 1. However, a lower finished part cost may be possible with such materials because of low basic material cost and/or lower fabrication costs. Thus, for certain cost-critical applications, a material that offers no weight savings may still be an attractive candidate.

Materials 7 through 11 are representative continuous-filament-reinforced matrix materials. Epoxy is high-polymer plastic with good mechanical properties up to about 250°F. The polyimide plastic matrix of Material 10 has comparable mechanical properties up to temperatures as high as 600°F but is presently slightly more expensive and difficult to work with than epoxy.

Two types of glass filaments, commonly designated as E glass and S glass, are in general use. The S glass is a higher-strength and,

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*Secondary structure includes such items as equipment mounting shelves, brackets, and similar non-flight-critical components.

**A thermoplastic polymer formed by copolymerizing acrylonitrile, butadiene, and styrene monomers.

Table 1

BASIC MATERIAL CHARACTERISTICS[a]

Structural Material Type	Approximate Weight Savings Versus Aluminum (percent)			Current Basic Material Cost ($/1b)	Typical Material Scrap Loss During Manufacture (percent)	Ratio of Typical Finished-Part Cost to Aluminum-Part Cost
	Fuselage	Wing or Tail	Secondary Structure			
1. Aluminum alloys	..	..	..	0.50-1.50	25	..
2. Steel alloys (including stainless)	-10	0	-50	0.50-2.50	25	1.1
3. Titanium alloys	15	10	0	3.50-15.00	25	2.2
4. Chopped E glass/polyester	-28	-30	15	0.63	5	0.8
5. Chopped S glass/epoxy	10	10	20	4.00	5	0.9
6. E glass fabric/epoxy	10	5	20	2.00	20	1.0
7. S glass/epoxy composite	20	15	30	4.00	5	1.1
8. Boron/epoxy composite	25	35	15	240.00	5	2.2
9. Graphite/epoxy composite	30	40	25	240.00	5	2.0
10. Graphite/polyimide composite	30	40	25	300.00	5	2.1
11. Boron- or graphite-filament-reinforced aluminum	25	30	15	400.00	10	3.0
12. Polyester-impregnated paper	7	-20	15	0.50	15	0.9
13. Unreinforced ABS plastic	-30	-36	-5	0.46	5	0.7
14. Wood (various hardwoods, solid or laminated)	12	10	20	0.65-2.00	15	1.1
15. Nylon fabric	5	50	N.A.	3.00	20	0.6

[a]Other possible materials for high-supersonic flight are considered in Table 17.

in particular, a higher-stiffness filament (about 12.4×10^6 psi versus about 10.5×10^6 psi for E glass). However, it is also about twice as expensive as E glass, although both are moderately low-cost (see Table 1).

The polyester plastic of Materials 4 and 12 has a lower cost but also poorer mechanical properties than epoxy, while its environmental resistance is equally good. Thus Material 4, incorporating the low-cost E glass filament and the low-cost polyester matrix, is a less expensive (but lower performance) material than either Material 6 or 5. Material 12, polyester-impregnated paper, is even less expensive because of the low cost of paper relative to that of glass filaments.

The chopped-glass-filament-reinforced plastic composites, Materials 4 and 5, are easily molded and result in low-cost finished parts. The same is true of the unreinforced ABS plastic, although its mechanical properties are considerably poorer than those of the reinforced materials (which shows up clearly in the weight-savings comparisons).

The fabric-reinforced plastic composites, exemplified by Material 6, are stronger and stiffer (particularly in the directions of the weave) than the chopped-filament-reinforced plastics but are not as readily fabricated. Correspondingly, they are easier to fabricate than the unidirectionally reinforced (nonwoven) composites but are not as strong or stiff.

Use of molding materials (4, 5, and 13) and tape-layup materials (7 through 10) results in very low scrap losses during manufacture. Scrap loss is a factor to consider in comparing their actual costs relative to those of materials utilized in other forms such as sheet, plate, and machined parts.

The metal matrix composite, Material 11, is included as an example of a very promising future airframe material. Continuous boron- or graphite-filament-reinforced aluminum is listed, since the development of aluminum matrix composites is presently the most advanced. However, other metals such as titanium and nickel are also very promising matrix materials and are being investigated at the present time. The very high current basic material cost and finished-part cost are primarily due to the limited quantities being produced and the high development costs still being included in cost quotations. These costs should decrease rapidly in the next several years.

Nylon fabric is not normally considered as a structural material, but it is included here because of its very specialized application to sail-wing vehicles. A very large weight savings is possible because of the minimum amount of structure required to support the flexible sail-wing.

The fifteen types of structural materials considered are compared in Table 2, on a relative ranking basis, in terms of a number of characteristic properties important to drone applications. Repairability refers to the relative ease of repair of damage that may occur during flight, recovery, or ground-handling.

Production-cost economies are associated with both the total number of units to be produced and the rate of production. For example, wood construction requires a considerable amount of hand labor. For small-quantity production, where large-scale fabrication equipment is not practical anyway, wood manufacturing costs can be comparable to those of many other materials. However, for large-quantity production, wood cannot compete with those materials that can be readily mass-produced. The unreinforced ABS plastic can be used in sheet form in small-quantity production, but like wood construction, this requires considerable hand labor. However, for large-quantity production, where the cost of molds and molding equipment can be justified, the cost per part of an ABS plastic-molded component can be greatly reduced, resulting in large production-cost economies.

Other materials can be economically produced in both small and large quantities by using different fabrication techniques. For example, the filament-reinforced composites, Materials 7 through 10, can be economically laid up by hand in sheet and tape form when only a few parts are to be made. For large-quantity production, automatic tape-laying or filament-winding equipment is available.

Table 2

RELATIVE RANKINGS OF CHARACTERISTIC MATERIAL PROPERTIES[a]

Structural Material Type	Cost	Weight	Fabric-ability	Specific Strength	Specific Stiffness	Temperature Resistance	Chemical Resistance	Fatigue Resistance	Repair-ability	Production Cost Economies: Small Quantities	Production Cost Economies: Large Quantities
1. Aluminum alloys	L	M	M	M	M	M	L	L	M	M	M
2. Steel alloys (including stainless)	L	H	M	M	M	H	L	L	M	M	H
3. Titanium alloys	M	M	L	M	M	H	M	M	L	M	H
4. Chopped E glass/polyester	L	L	M	M	L	L	H	H	H	H	H
5. Chopped S glass/epoxy	M	L	H	M	M	L	H	H	H	H	H
6. E glass fabric/epoxy	L	L	H	M	M	L	H	M	H	H	M
7. S glass/epoxy composite	M	L	H	H	M	L	H	H	H	H	H
8. Boron/epoxy composite	H	L	H	H	H	L	H	H	H	H	H
9. Graphite/epoxy composite	H	L	H	H	H	L	H	H	H	H	H
10. Graphite/polyimide composite	H	L	H	H	H	M	H	H	H	H	H
11. Boron- or graphite-filament-reinforced aluminum	H	M	L	H	H	M	L	H	M	L	M
12. Polyester-impregnated paper	L	L	H	L	L	L	M	M	H	M	L
13. Unreinforced ABS plastic	L	L	H	L	L	L	M	M	M	M	H
14. Wood (various hardwoods, solid or laminated)	L	L	H	M	M	L	L	M	H	M	L
15. Nylon fabric	M	L	H	L	L	L	H	M	H	M	L

[a] H = high, M = medium, L = low.

III. APPLICABILITY TO SPECIFIC MISSIONS

Not all of the materials considered can be utilized for the full range of missions of interest. For example, the unreinforced ABS plastic, having low strength and low stiffness, is quite adequate for low-loading conditions; but ABS plastic components designed to resist more severe airframe loadings would be prohibitively bulky (thick) and thus impractical.

At the other extreme are materials such as the boron- or graphite-filament-reinforced epoxy (or polyimide) composites, which have very high strength and stiffness properties and are thus ideally suited for highly loaded structures. But the required thicknesses for lightly loaded structures may be so small as to be impractical (or impossible) to fabricate and handle. Obviously, when "minimum-gauge thickness limitations" are encountered, more high-strength material must be used than is necessary to carry the loads, and thus both weight and cost penalties are encountered.

Table 3 has been constructed with these types of considerations in mind. The primary emphasis of the present study is on air-launch and recovery conditions, which are considered as moderate in this and subsequent tables. However, more severe conditions such as would be encountered during ground launch (e.g., by catapult) and particularly during ground recovery (e.g., landing on wheels or skids) or ground impact via a parachute descent are also included for comparison.

Two supersonic cruise speeds are included in Table 3; Mach 2.3 and Mach 3.0. The primary difference is the amount of aerodynamic heating encountered. Temperatures at the vehicle surface of 295°F to 355°F are typical for the Mach 2.3 cruise vehicle versus 550°F to 650°F for the Mach 3.0 cruise vehicle. As will be discussed in more detail later, the higher temperatures associated with supersonic flight will limit or eliminate many materials, including the aluminum alloys. In Table 3 and subsequent tables, no distinction is made between moderate and severe loading conditions for supersonic flight.

Whereas Table 3 summarizes the potential application of the various materials to the complete airframe structure for various flight conditions,

Table 3

MATERIALS APPLICABILITY FOR SPECIFIC MISSION REQUIREMENTS[a]

Structural Material Type	Cruising Speed and Severity of Loading Conditions					
	Subsonic				Supersonic	
	Mach 0.15		Mach 0.5-0.9		Mach 2.3	Mach 3.0
	Moderate	Severe	Moderate	Severe	Moderate and Severe	Moderate and Severe
1. Aluminum alloys	H	H	H	H	H	L
2. Steel alloys (including stainless)	-	L	L	L	H	H
3. Titanium alloys	-	-	L	L	H	H
4. Chopped E glass/polyester	H	H	L	-	-	-
5. Chopped S glass/epoxy	H	H	H	L	-	-
6. E glass fabric/epoxy	H	H	L	-	-	-
7. S glass/epoxy composite	L	H	H	H	L	-
8. Boron/epoxy composite	-	-	L	H	H	L
9. Graphite/epoxy composite	-	-	L	H	H	L
10. Graphite/polyimide composite	-	-	-	-	H	H
11. Boron- or graphite-filament-reinforced aluminum	-	-	-	-	H	L
12. Polyester-impregnated paper	H	L	-	-	-	-
13. Unreinforced ABS plastic	H	L	-	-	-	-
14. Wood (various hardwoods, solid or laminated)	H	L	-	-	-	-
15. Nylon fabric	H	L	-	-	-	-

[a]H = high rating on basis of combined weight and cost; L = lower rating on basis of combined weight and cost; (-) = not applicable.

Tables 4 through 7 indicate their applicability to specific components of the structure. The same considerations apply, however, viz., cost, excessive bulk, minimum-gauge limitations, operating temperatures, etc.

Table 4

MATERIALS APPLICABILITY[a]: MACH 0.15 TO MACH 0.30 CRUISE VEHICLE, MODERATE AND SEVERE LOADS

Structural Material Type	Fuselage, Wing, Empennage			Engine Nacelles	Inlet Ducts	Engine Exhaust Areas	Fairings	Secondary Structure	Fuel Tanks
	Skins	Frames	Fittings						
Moderate Loads									
1. Aluminum alloys	L	L	H	L	-	L	-	L	H
2. Steel alloys (including stainless)	-	-	L	-	-	H	-	L	L
3. Titanium alloys	-	-	-	-	-	-	-	-	-
4. Chopped E glass/polyester	H	H	L	L	H	-	H	H	L
5. Chopped S glass/epoxy	H	H	H	H	H	-	H	H	H
6. E glass fabric/epoxy	H	H	-	H	L	-	H	H	L
7. S glass/epoxy composite	L	L	-	-	-	-	-	-	L
8. Boron/epoxy composite	-	-	-	-	-	-	-	-	-
9. Graphite/epoxy composite	-	-	-	-	-	-	-	-	-
10. Graphite/polyimide composite	-	-	-	-	-	-	-	-	-
11. Boron- or graphite-filament-reinforced aluminum	-	-	-	-	-	-	-	-	-
12. Polyester-impregnated paper	H	-	-	L	L	-	L	L	H
13. Unreinforced ABS plastic	H	L	L	L	L	-	H	L	-
14. Wood (various hardwoods, solid or laminated)	L	H	-	-	L	-	H	L	-
15. Nylon fabric	H	-	-	-	-	-	-	-	-
Severe Loads									
1. Aluminum alloys	H	H	H	H	-	L	-	L	H
2. Steel alloys (including stainless)	-	-	L	-	-	H	-	L	L
3. Titanium alloys	-	-	-	-	-	-	-	-	-
4. Chopped E glass/polyester	L	L	-	-	H	-	H	H	-
5. Chopped S glass/epoxy	H	L	L	H	H	-	H	H	L
6. E glass fabric/epoxy	H	H	-	L	L	-	H	H	-
7. S glass/epoxy composite	H	L	-	L	-	-	-	-	H
8. Boron/epoxy composite	-	-	-	-	-	-	-	-	-
9. Graphite/epoxy composite	-	-	-	-	-	-	-	-	-
10. Graphite/polyimide composite	-	-	-	-	-	-	-	-	-
11. Boron- or graphite-filament-reinforced aluminum	-	-	-	-	-	-	-	-	-
12. Polyester-impregnated paper	L	-	-	-	L	-	L	L	L
13. Unreinforced ABS plastic	L	-	-	-	-	-	L	-	-
14. Wood (various hardwoods, solid or laminated)	-	L	-	-	L	-	L	L	-
15. Nylon fabric	L	-	-	-	-	-	-	-	-

[a]H = high rating on basis of combined weight and cost; L = lower rating on basis of combined weight and cost; (-) = not applicable.

Table 5

MATERIALS APPLICABILITY[a]: MACH 0.5 TO MACH 0.9 CRUISE VEHICLE, MODERATE AND SEVERE LOADS

Structural Material Type	Fuselage, Wing, Empennage			Engine Nacelles	Inlet Ducts	Engine Exhaust Areas	Fairings	Secondary Structure	Fuel Tanks
	Skins	Frames	Fittings						
Moderate Loads									
1. Aluminum alloys	H	H	H	H	H	L	-	H	H
2. Steel alloys (including stainless)	-	-	L	-	-	H	-	L	L
3. Titanium alloys	-	-	-	-	-	-	-	-	-
4. Chopped E glass/polyester	L	L	-	L	H	-	H	H	-
5. Chopped S glass/epoxy	H	L	L	H	H	-	H	H	L
6. E glass fabric/epoxy	L	L	-	L	L	-	H	H	-
7. S glass/epoxy composite	H	L	-	H	-	-	-	L	H
8. Boron/epoxy composite	L	-	-	-	-	-	-	-	-
9. Graphite/epoxy composite	L	-	-	-	-	-	-	-	-
10. Graphite/polyimide composite	-	-	-	-	-	L	-	-	-
11. Boron- or graphite-filament reinforced aluminum	-	-	-	-	-	-	-	-	-
12. Polyester-impregnated paper	L	-	-	-	L	-	L	L	L
13. Unreinforced ABS plastic	-	-	-	-	L	-	-	-	-
14. Wood (various hardwoods, solid or laminated)	-	L	-	-	L	-	L	L	-
15. Nylon fabric	L	-	-	-	-	-	-	-	-
Severe Loads									
1. Aluminum alloys	H	H	H	H	L	L	-	H	H
2. Steel alloys (including stainless)	-	-	H	-	-	H	-	L	L
3. Titanium alloys	-	-	L	-	-	-	-	-	-
4. Chopped E glass/polyester	L	-	-	L	H	-	H	H	-
5. Chopped S glass/epoxy	L	-	-	L	H	-	H	H	-
6. E glass fabric/epoxy	H	L	-	H	L	-	H	H	-
7. S glass/epoxy composite	H	H	-	H	-	-	-	L	H
8. Boron/epoxy composite	L	L	-	L	-	-	-	-	-
9. Graphite/epoxy composite	L	L	-	L	-	-	-	-	-
10. Graphite/polyimide composite	-	-	-	-	-	L	-	-	-
11. Boron- or graphite-filament reinforced aluminum	-	-	-	-	-	-	-	-	-
12. Polyester-impregnated paper	-	-	-	-	-	-	-	-	-
13. Unreinforced ABS plastic	-	-	-	-	-	-	-	-	-
14. Wood (various hardwoods, solid or laminated)	-	-	-	-	-	-	-	-	-
15. Nylon fabric	-	-	-	-	-	-	-	-	-

[a]H = high rating on basis of combined weight and cost; L = lower rating on basis of combined weight and cost; (-) = not applicable.

Table 6

MATERIALS APPLICABILITY[a]: MACH 2.3 CRUISE VEHICLE, MODERATE AND SEVERE LOADS

Structural Material Type	Fuselage, Wing, Empennage Skins	Fuselage, Wing, Empennage Frames	Fuselage, Wing, Empennage Fittings	Engine Nacelles	Inlet Ducts	Engine Exhaust Areas	Fairings	Secondary Structure	Fuel Tanks
1. Aluminum alloys	H	H	H	H	L	L	L	H	H
2. Steel alloys (including stainless)	L	L	H	L	-	H	-	L	L
3. Titanium alloys	L	L	H	L	-	H	-	L	L
4. Chopped E glass/polyester	-	-	-	-	-	-	-	L	-
5. Chopped S glass/epoxy	-	-	-	-	L	-	L	L	-
6. E glass fabric/epoxy	-	-	-	-	L	-	L	H	-
7. S glass/epoxy composite	-	H	L	-	-	-	-	H	H
8. Boron/epoxy composite	-	H	L	-	-	-	-	H	-
9. Graphite/epoxy composite	-	H	L	-	-	-	-	H	-
10. Graphite/polyimide composite	H	H	L	H	H	H	H	L	L
11. Boron- or graphite-filament reinforced aluminum	H	H	L	H	L	L	-	L	L
12. Polyester-impregnated paper	-	-	-	-	-	-	-	-	-
13. Unreinforced ABS plastic	-	-	-	-	-	-	-	-	-
14. Wood (various hardwoods, solid or laminated)	-	-	-	-	-	-	-	-	-
15. Nylon fabric	-	-	-	-	-	-	-	-	-

[a] H = high rating on basis of combined weight and cost; L = lower rating on basis of combined weight and cost; (-) = not applicable.

Table 7

MATERIALS APPLICABILITY[a]: MACH 3.0 CRUISE VEHICLE, MODERATE AND SEVERE LOADS

Structural Material Type	Fuselage, Wing, Empennage			Engine Nacelles	Inlet Ducts	Engine Exhaust Areas	Fairings	Secondary Structure	Fuel Tanks
	Skins	Frames	Fittings						
1. Aluminum alloys	-	L	L	-	-	-	-	H	H
2. Steel alloys (including stainless)	H	H	H	H	H	H	-	L	L
3. Titanium alloys	H	H	H	H	H	H	-	H	H
4. Chopped E glass/polyester	-	-	-	-	-	-	-	-	-
5. Chopped S glass/epoxy	-	-	-	-	-	-	-	L	-
6. E glass fabric/epoxy	-	-	-	-	-	-	-	-	-
7. S glass/epoxy composite	-	-	-	-	-	-	-	-	L
8. Boron/epoxy composite	-	-	-	-	-	-	-	-	-
9. Graphite/epoxy composite	-	-	-	-	-	-	-	-	-
10. Graphite/polyimide composite	H	H	L	H	H	L	H	H	H
11. Boron- or graphite-filament-reinforced aluminum	-	L	L	-	-	-	-	H	H
12. Polyester-impregnated paper	-	-	-	-	-	-	-	-	-
13. Unreinforced ABS plastic	-	-	-	-	-	-	-	-	-
14. Wood (various hardwoods, solid or laminated)	-	-	-	-	-	-	-	-	-
15. Nylon fabric	-	-	-	-	-	-	-	-	-

[a] H = high rating on basis of combined weight and cost; L = lower rating on basis of combined weight and cost; (-) = not applicable.

IV. TYPICAL AIRFRAME-MATERIAL COMBINATIONS

The material combinations considered here are representative of those currently available for subsonic- and low-supersonic-cruise vehicle applications and were selected to emphasize the performance of a particular material, or to attain a particular objective, e.g., low cost or low weight. Effects of elevated-temperature environments (typical of high-supersonic-cruise vehicles) will be considered later. Obviously, other combinations of the same materials, or additional materials, could also be considered. However, those presented here are believed to cover the range of possibilities reasonably well.

All rankings are in relation to all-aluminum structures, and broad comparatives have been used, e.g., moderately increased, greatly increased, moderately decreased, and greatly decreased. The extreme cases for a particular characteristic are also indicated, e.g., highest and lowest.

While the primary emphasis here is on weight comparisons, airframe cost and durability are also compared in the following brief discussions of nine potentially applicable material combinations. Durability is loosely defined to include such factors as resistance to damage due to ground handling, adverse flight and storage environments, and structural fatigue. Also included are relative ease of maintenance, inspection, and repair, all of which are important factors in multiple-flight drone applications.

ALUMINUM

The weights of the individual structural components for the all-aluminum configurations, which will be used as the bases of comparisons for all the subsonic-cruise vehicles, have been estimated by the design method previously described. Since few actual design data points are currently available for the relatively small vehicles being analyzed here, these weights were obtained using appropriate performance scaling factors. These typically require extrapolations rather than interpolations. Thus, the construction methods for these small airframes may be different from those used in larger vehicles. For example, greater use of ring-stiffened monocoque fuselages and full-depth honeycomb-core wing and tail structures can be anticipated; the component weights of the aluminum structures indicated here assume the most efficient construction method is used for the particular application. Another problem, that of encountering minimum-gauge limitations, has not been explicitly considered. Some weight estimates would have to be increased if such limitations were encountered in an actual detailed design. The same consideration will also apply to the other material combinations being considered, however.

FIBERGLASS

Fiberglass construction, like all-aluminum construction, represents an adequately proven state of the art. The increased durability of fiberglass is due in part to the absence of corrosion problems and the ease of repair of minor damage. Fiberglass has an outstanding strength-to-weight ratio, but only an average stiffness-to-weight ratio, Hence, it is most advantageously utilized in strength-critical structures. A moderate overall weight reduction can be expected. Although its basic material cost is higher than that of aluminum, fabrication costs are at least comparable. Hence, the cost of a finished part is, at most, only moderately higher. Fiberglass/epoxy is a radar-transparent material, while aluminum is not.

FIBERGLASS WITH PAPER HONEYCOMB CORE

Replacing the S glass/epoxy wing of an all-fiberglass design with a paper phenolic honeycomb-core/aluminum-skin wing offers an additional weight reduction and a lower cost. The paper phenolic honeycomb core precludes the possibility of a wet wing, however. It is also a less rugged construction than the S glass/epoxy sheet and spar construction, and thus provides lower system reliability. Another alternative would be the use of unidirectional S glass wing skins in place of the aluminum, particularly for radar-cross-section reduction. This combination is comparable to aluminum in cost and durability.

CAST AND MOLDED PLASTICS

Chopped E glass/polyester centrifugally cast tubing of the required size is commercially available. Its use will require a constant fuselage diameter and specially cast nose and tail closures. However, a specially cast entire fuselage (in two or three sections) is a possible alternative. The actual cost of the ABS molded plastic wing will depend somewhat upon the quantities produced because of the high nonrecurring costs of the required molding equipment. Because of the poor elevated-temperature properties of polyester, the engine nacelle would be of standard aluminum construction. The total airframe weight would be high because of the relatively low strength and stiffness characteristics of these plastic materials. The resulting airframe, except the aluminum nacelle, would be radar-transparent, however. Cost would be greatly reduced and durability moderately increased.

PAPER AND FOAM

The combination of paper and foam can be expected to lead to greatly reduced cost and moderately reduced weight, but low durability. Polyester-impregnated, spiral-wound paper tubing in the required size is commercially available. Nose and tail cones to close out the constant-diameter midsection must be specially molded, using chopped-E-glass-reinforced or unreinforced polyester moldings. The polyurethane-foamed wing has natural skins and hence limited durability. As in the cast and molded plastic combination, standard aluminum nacelle construction would be used.

WOOD

Wood construction can be expected to lead to moderately reduced weight, moderately increased cost, and moderately reduced durability. Sitka spruce has good stiffness-to-weight properties and is an excellent framing material. Mahogany plywood has good shear properties and is an efficient skin-covering material. The combination results in a lighter structure than aluminum. Fabrication costs would be higher though, and wood requires frequent maintenance, e.g., refinishing. Like the plastics, it is radar-transparent.

SAIL-WING DESIGN

For those limited missions where it is applicable, e.g., high-altitude, low-speed missions, the sail-wing offers a significant weight savings, as well as lower cost. Nylon cloth has been assumed here but other fabrics can also be utilized. The stowability of a flexible wing can be an advantage in certain launch and recovery systems. Obviously, the sail-wing could be combined with fiberglass/epoxy fuselage and tail structures to reduce the total airframe weight even more. This would also increase the radar transparency but would increase the cost. Durability of sail-wings may be low.

GRAPHITE-FILAMENT/EPOXY COMPOSITES

Graphite-filament/epoxy composites are expected to have the lowest weight, greatly increased durability, and the highest cost. Graphite/epoxy has a very low density and high strength and stiffness properties. Graphite filament presently costs about $240/lb. However, fabrication costs are comparable to those of aluminum. This material is included to indicate the present potential of filament-reinforced composites. The near-term (2- to 5-year) cost-reduction potential of this material is very high; and eventual costs as low as $1.00 to $2.00/lb are being projected, which are near the current $0.50 to $1.50/lb cost of aluminum alloys. Boron filament offers similar high performance, at a comparable high cost. However, the near-term cost-reduction potential is much less.

TITANIUM ALLOYS

Use of titanium alloys would lead to moderately reduced weight and moderately increased durability, but greatly increased costs. Titanium, like graphite/epoxy, is not a cost-effective material for low-performance drone applications. Only when weight savings become extremely important, as for very high-altitude operation, or when thermal environments become severe, as beyond about Mach 2.5, can titanium compete with or replace aluminum. Both material cost and fabrication costs are high relative to those of aluminum. Unlike graphite/epoxy, titanium does not appear to have a large cost-reduction potential in the near future.

OTHER POSSIBILITIES

Steel alloys were included in Tables 1 through 7 for comparison purposes but have not been specifically discussed. Having specific strengths and stiffnesses comparable to those of aluminum but being almost three times as dense, steel alloys are subject to minimum-gauge limitations in the low-performance applications being considered here.

Graphite/polyimide composites have room-temperature mechanical properties comparable to those of the graphite/epoxy composites (as do the various other polyimide matrix composites when compared to their epoxy matrix counterparts). Since, as Table 1 indicates, they are both slightly more expensive and more difficult to fabricate, they would not normally be used in place of the epoxy-matrix composites when temperature is not a consideration. Thus, they have not been discussed here.

The high cost and lack of well-developed fabrication processes for filaments tend to eliminate the boron- or graphite-filament-reinforced aluminum composites from current applications to subsonic vehicles. However, even as the cost of the filaments is reduced and better fabrication methods are established, the metal matrix composites will probably not be competitive with the plastic matrix composites for subsonic vehicles. Because of their higher density (aluminum is about twice as dense as epoxy), smaller weight savings are probable, as indicated in Table 1.

Beryllium offers weight advantages in the subsonic and low supersonic range. It is costly, has low ductility, and poses fabrication problems. Although it was not included in this study, there may be applications for this material.

V. AIRFRAME STRUCTURAL WEIGHT COMPARISONS FOR VARIOUS MATERIAL COMBINATIONS

The nine combinations described above will now be considered for specific drone applications and compared on a detailed structural-weight basis. Subsonic cruise vehicles will be compared separately from supersonic vehicles, since aerodynamic heating effects are negligible for subsonic flight. Many of the material combinations considered have a very limited elevated-temperature resistance and must be eliminated from consideration for supersonic cruise vehicles on this basis alone. Other, more suitable materials will be introduced as required.

The weights of the individual structural components for an assumed basic vehicle configuration were obtained using a design analysis developed at Rand.[1] The total weight of the tail assembly is assumed to be 25 percent that of the wing. The weight of the nacelle is assumed to be 7-1/2 percent that of the engine for the subsonic drones, and 10 percent for the supersonic drones.

SUBSONIC CRUISE VEHICLES

Five specific subsonic drone configurations will be analyzed in detail here. These configurations, generated using a design method developed at Rand,[1] have been chosen to be representative of vehicles designed for a number of types of drone missions. Their characteristics and performance are given in Table 8.

The first two configurations are designed for low-speed, moderately high-altitude (55,000 ft), long-endurance missions; the principal difference between them is the type of propulsion system used. Configurations 3, 4, and 5 are designed for high-subsonic-speed cruise missions--Configuration 3 for low-altitude, 1000-n mi range, and 4 and 5 for high-altitude (75,000 ft), long range (2500 and 5500 n mi, respectively).

The influences of both cruise speed and launch and recovery loads on materials selection were indicated qualitatively in Tables 3 through 7. It was shown that the low-performance (and typically low-cost) materials are most likely to be considered for subsonic-cruise-speed

Table 8

CHARACTERISTICS OF REPRESENTATIVE SUBSONIC CRUISE VEHICLES SELECTED FOR ANALYSIS

Configuration	Cruise Speed (kn)	Cruise Altitude (ft)	Cruise Endurance (hr)	Cruise Range (n mi)	Gross Weight[a] (lb)	Payload Weight[b] (lb)	Structural Weight[a] (lb)	Engine
1	172	55,000	21.5	..	6,000	700	1,760	Reciprocating prop
2	273	55,000	23.7	..	3,500	700	623	Turboprop
3	500	Sea level	..	1000	2,000	350	288	Turbofan
4	515	75,000	..	2500	3,000	700	653	Turbofan
5	515	75,000	..	5500	8,000	700	1,985	Turbofan

[a]For all-aluminum construction, base case.

[b]Includes guidance and navigation systems.

drones and moderate design load factors. Configurations 1 through 5 all assume moderate design loads. The most significant effect of changing this to a more severe loading would be an increase in the structural weight fraction as the airframe is strengthened to carry the additional loads. This increase in structural weight would correspondingly increase the potential for total weight savings obtainable by materials substitution.

Detailed structural-weight breakdowns for the five subsonic cruise vehicles are presented in Tables 9 through 13. The numbers in parentheses under the heading "Weight of Structural Component" indicate the fractions of the weight of the all-aluminum component which have been assumed to be attainable by the indicated materials substitution. These fractions are based in part upon the weight-savings estimates presented in Table 1 for individual materials. They are also influenced by actual detail design studies, as referenced. Obviously the values tabulated here, as well as those given in Table 1, must be considered only as typical values. A detailed design study of each component of a specific configuration is necessary to obtain specific weight estimates.

These weight fractions are then used to compute the component weights indicated. The last two columns indicate, respectively, the total weight of the airframe structure for each material combination (and, in parentheses, this weight as a fraction of the weight of the all-aluminum configuration) and the total weight change from the all-aluminum configuration (and, in parentheses, this change as a percentage of the all-aluminum-configuration total weight). Only the cast and molded plastic material combination results in a net weight increase. As suggested earlier, this combination is included because of its potential for low cost.

Although the airframe loadings for the drone missions being considered here are not severe, the importance of reducing structural weight as the mission becomes more taxing can be appreciated by comparing Configurations 1 and 2. As previously stated, the mission for these two designs is the same, viz., long-endurance flight at 55,000 ft altitude. However, a reciprocating engine is assumed in

Table 9

STRUCTURAL WEIGHTS FOR SUBSONIC CRUISE VEHICLES: CONFIGURATION 1[a]

Material Combination	Weight of Structural Component (lb)[b]					Total Weight of Structure (lb)[b]	Total Weight Change (lb)[c]
	Fuselage	Wing	Tail	Nacelle	Reference		
All aluminum							
Conventional aluminum construction (base case)	237	1185	296	42	..	1760	..
All fiberglass							
Chopped S glass/epoxy skins S glass filament/epoxy substructure	202 (0.85)	..	..	36 (0.85)	2 (p. 66)	..	..
S glass filament and E glass fabric/epoxy layup	..	1067 (0.90)	..	..	2 (p. 67)	..	..
Chopped S glass/epoxy molded	..	..	252 (0.85)	..	2 (p. 61)	1557 (0.88)	-203 (-11.5)
Fiberglass - paper honeycomb							
Chopped S glass/epoxy skins S glass filament/epoxy substructure	202 (0.85)	..	..	36 (0.85)	2 (p. 66)	..	..
Paper phenolic honeycomb cora, aluminum skins	..	972 (0.82)	243 (0.82)	..	3 (p. I-55)	1453 (0.83)	-307 (-17.4)
Cast and molded plastics							
Chopped E glass/polyester centrifugally cast tube	304 (1.28)	..	..	..	3 (p. I-27)	..	..
ABS molded plastic with aluminum fittings	..	1611 (1.36)	403 (1.36)	..	3 (p. I-52)	..	..
Aluminum - conventional construction	..	..	..	42 (1.00)	..	2360 (1.34)	600 (34.1)
Paper and foam							
Polyester-impregnated, spiral-wound paper tube	220 (0.93)	..	..	..	3 (p. I-2[illegible])	..	..
Polyurethane foam (natural skin) with aluminum spara	..	960 (0.81)	240 (0.81)	..	3 (p. I-53)	..	..
Aluminum - conventional construction	..	..	..	42 (1.00)	..	1462 (0.83)	-298 (-16.9)
Wood							
Sitka spruce substructure, mahogany plywood skins	209 (0.88)	1067 (0.90)	266 (0.90)	42 (1.00)	2 (pp. 27-28)	1584 (0.90)	-176 (-10.0)
Sail-wing							
Nylon fabric sail-wing, aluminum frames, nylon fuselage and tail coverings	226 (0.95)	593 (0.50)	266 (0.90)	42 (1.00)	2 (p. 19)	1127 (0.64)	-633 (-35.9)
Graphite filament							
Graphite filament/epoxy (maximum utilization), glass filament or fabric/ epoxy whera applicable	178 (0.75)	711 (0.60)	222 (0.75)	32 (0.75)	4 (pp. 377-382)	1143 (0.65)	-617 (-35.0)
Titanium							
Titanium (maximum utilization), aluminum where applicable	202 (0.85)	1067 (0.90)	266 (0.90)	36 (0.85)	(d)	1571 (0.89)	-189 (-10.7)

[a]Altitude = 55,000 ft; apeed = 172 kn; endurance = 21.5 hr; payload = 700 lb; groaa weight = 6000 lb; reciprocating-prop engine.

[b]Numbers in paranthesea indicate tha fraction of the all-aluminum-component weight.

[c]Numbers in parentheses indicata tha parcantage of the all-aluminum-configuration total weight.

[d]Unpublished work by J. R. Gebman, The Rand Corporation.

Table 10

STRUCTURAL WEIGHTS FOR SUBSONIC CRUISE VEHICLES: CONFIGURATION 2[a]

Material Combination	Weight of Structural Component (lb)[b] Fuselage	Wing	Tail	Nacelle	Reference	Total Weight of Structure (lb)[b]	Total Weight Change (lb)[c]
All aluminum							
Conventional aluminum construction (base case)	188	333	83	19	..	623	..
All fiberglass							
Chopped S glass/epoxy skins							
S glass filament/epoxy substructure	160 (0.85)	..	..	16 (0.85)	2 (p. 66)	..	..
S glass filament and E glass fabric/epoxy layup	..	300 (0.90)	..	..	2 (p. 67)	..	..
Chopped S glass/epoxy molded	..	..	71 (0.85)	..	2 (p. 61)	547 (0.88)	-76 (-12.2)
Fiberglass - paper honeycomb							
Chopped S glass/epoxy skins							
S glass filament/epoxy substructure	160 (0.85)	..	..	16 (0.85)	2 (p. 66)	..	..
Paper phenolic honeycomb core, aluminum skins	..	274 (0.82)	68 (0.82)	..	3 (p. 1-55)	518 (0.83)	-105 (-16.8)
Cast and molded plastics							
Chopped E glass/polyester centrifugally cast tube	241 (1.28)	..	..	..	3 (p. 1-27)	..	..
ABS molded plastic with aluminum fittings	..	453 (1.36)	113 (1.36)	..	3 (p. 1-52)	..	..
Aluminum - conventional construction	..	..	..	19 (1.00)	..	826 (1.33)	203 (32.6)
Paper and foam							
Polyester-impregnated, spiral-wound paper tube	175 (0.93)	..	..	..	3 (p. 1-26)	..	..
Polyurethane foam (natural skin) with aluminum spars	..	271 (0.81)	68 (0.81)	..	3 (p. 1-53)	..	..
Aluminum - conventional construction	..	..	..	19 (1.00)	..	533 (0.86)	-90 (-14.5)
Wood							
Sitka spruce substructure, mahogany plywood skins	165 (0.88)	300 (0.90)	75 (0.90)	19 (1.00)	2 (pp. 27-28)	559 (0.90)	-64 (-10.3)
Sail-wing							
Nylon fabric sail-wing, aluminum frames, nylon fuselage and tail coverings	179 (0.95)	167 (0.50)	75 (0.90)	19 (1.00)	2 (p. 19)	440 (0.71)	-183 (-29.4)
Graphite filament							
Graphite filament/epoxy (maximum utilization), glass filament or fabric/epoxy where applicable	141 (0.75)	200 (0.60)	62 (0.75)	14 (0.75)	4 (pp. 377-382)	417 (0.67)	-206 (-33.1)
Titanium							
Titanium (maximum utilization), aluminum where applicable	160 (0.85)	300 (0.90)	75 (0.90)	16 (0.85)	(d)	551 (0.88)	-72 (-11.6)

[a]Altitude = 55,000 ft; speed = 273 kn; endurance = 23.7 hr; payload = 700 lb; gross weight = 3500 lb; turboprop engine.

[b]Numbers in parentheses indicate the fraction of the all-aluminum-component weight.

[c]Numbers in parentheses indicate the percentage of the all-aluminum-configuration total weight.

[d]Unpublished work by J. R. Gebman, The Rand Corporation.

Table 11

STRUCTURAL WEIGHTS FOR SUBSONIC CRUISE VEHICLES: CONFIGURATION 3[a]

Material Combination	Weight of Structural Component (lb)[b] Fuselage	Wing	Tail	Nacelle	Reference	Total Weight of Structure (lb)[b]	Total Weight Change (lb)[c]
All aluminum							
Conventional aluminum construction (base case)	250	26	6	6	..	288	..
All fiberglass							
Chopped S glass/epoxy skins							
S glass filament/epoxy substructure	212 (0.85)	..	..	5 (0.85)	2 (p. 66)	..	..
S glass filament and E glass fabric/epoxy layup	..	23 (0.90)	..	..	2 (p. 67)	..	..
Chopped S glass/epoxy molded	..	..	5 (0.85)	..	2 (p. 61)	245 (0.85)	-43 (-14.9)
Fiberglass - paper honeycomb							
Chopped S glass/epoxy skins							
S glass filament/epoxy substructure	212 (0.85)	..	..	5 (0.85)	2 (p. 66)	..	..
Paper phenolic honeycomb core, aluminum skins	..	21 (0.82)	5 (0.82)	..	3 (p. I-55)	243 (0.84)	-45 (-15.6)
Cast and molded plastics							
Chopped E glass/polyester centrifugally cast tube	320 (1.28)	..	..	..	3 (p. I-27)	..	..
ABS molded plastic with aluminum fittings	..	35 (1.36)	8 (1.36)	..	3 (p. I-52)	..	..
Aluminum - conventional construction	..	..	..	6 (1.00)	..	369 (1.28)	81 (28.1)
Paper and foam							
Polyester-impregnated, spiral-wound paper tube	232 (0.93)	..	..	..	3 (p. I-26)	..	..
Polyurethane foam (natural skin) with aluminum spars	..	21 (0.81)	5 (0.81)	..	3 (p. I-53)	..	..
Aluminum - conventional construction	..	..	..	6 (1.00)	..	264 (0.92)	-24 (-8.3)
Wood							
Sitka spruce substructure, mahogany plywood skins	220 (0.88)	23 (0.90)	5 (0.90)	6 (1.00)	2 (pp. 27-28)	254 (0.88)	-34 (-11.8)
Sail-wing							
Nylon fabric sail-wing, aluminum frames, nylon fuselage and tail coverings	..	..	..	..	..	..	..
Graphite filament							
Graphite filament/epoxy (maximum utilization), glass filament or fabric/epoxy where applicable	188 (0.75)	16 (0.60)	4 (0.75)	5 (0.75)	4 (pp. 377-382)	213 (0.74)	-75 (-26.0)
Titanium							
Titanium (maximum utilization), aluminum where applicable	212 (0.85)	23 (0.90)	5 (0.90)	6 (0.85)	(d)	246 (0.85)	-42 (-14.6)

[a] Sea level; speed = 500 kn; range = 1000 n mi; payload = 350 lb; gross weight = 2000 lb; turbofan engine.

[b] Numbers in parentheses indicate the fraction of the all-aluminum-component weight.

[c] Numbers in parentheses indicate the percentage of the all-aluminum-configuration total weight.

[d] Unpublished work by J. R. Gebman, The Rand Corporation.

Table 12

STRUCTURAL WEIGHTS FOR SUBSONIC CRUISE VEHICLES: CONFIGURATION 4[a]

Material Combination	Weight of Structural Component (lb)[b] Fuselage	Wing	Tail	Nacelle	Reference	Total Weight of Structure (lb)[b]	Total Weight Change (lb)[c]
All aluminum							
Conventional aluminum construction (base case)	189	345	86	33	..	653	..
All fiberglass							
Chopped S glass/epoxy skins							
S glass filament/epoxy substructure	161 (0.85)	..	..	28 (0.85)	2 (p. 66)	..	..
S glass filament and E glass fabric/epoxy layup	..	310 (0.90)	..	..	2 (p. 67)	..	..
Chopped S glass/epoxy molded	..	..	73 (0.85)	..	2 (p. 61)	572 (0.88)	-81 (-12.4)
Fiberglass - paper honeycomb							
Chopped S glass/epoxy skins							
S glass filament/epoxy substructure	161 (0.85)	..	..	28 (0.85)	2 (p. 66)	..	..
Paper phenolic honeycomb core, aluminum skins	..	283 (0.82)	70 (0.82)	..	3 (p. I-55)	542 (0.83)	-111 (-17.0)
Cast and molded plastics							
Chopped E glass/polyester centrifugally cast tube	242 (1.28)	..	..	..	3 (p. 1-27)	..	..
ABS molded plastic with aluminum fittings	..	469 (1.36)	117 (1.36)	..	3 (p. I-52)	..	..
Aluminum - conventional construction	..	..	..	33 (1.00)	..	861 (1.32)	208 (31.9)
Paper and foam							
Polyester-impregnated, spiral-wound paper tube	176 (0.93)	..	..	..	3 (p. I-26)	..	..
Polyurethane foam (natural skin) with aluminum spars	..	279 (0.81)	70 (0.81)	..	3 (p. I-53)	..	..
Aluminum - conventional construction	..	..	..	33 (1.00)	..	558 (0.85)	-95 (-14.6)
Wood							
Sitka spruce substructure, mahogany plywood skins	166 (0.88)	310 (0.90)	77 (0.90)	33 (1.00)	2 (pp. 27-28)	586 (0.90)	-67 (-10.3)
Sail-wing							
Nylon fabric sail-wing, aluminum frames, nylon fuselage and tail coverings	180 (0.95)	173 (0.50)	77 (0.90)	33 (1.00)	2 (p. 19)	463 (0.71)	-190 (-29.1)
Graphite filament							
Graphite filament/epoxy (maximum utilization), glass filament or fabric/epoxy where applicable	142 (0.75)	207 (0.60)	64 (0.75)	25 (0.75)	4 (pp. 377-382)	438 (0.67)	-215 (-33.0)
Titanium							
Titanium (maximum utilization), aluminum where applicable	161 (0.85)	310 (0.90)	77 (0.90)	28 (0.85)	(d)	576 (0.88)	-77 (-11.8)

[a]Altitude = 75,000 ft; speed = 515 kn; range = 2500 n mi; payload = 700 lb; gross weight = 3000 lb; turbofan engine.

[b]Numbers in parentheses indicate the fraction of the all-aluminum-component weight.

[c]Numbers in parentheses indicate the percentage of the all-aluminum-configuration total weight.

[d]Unpublished work by J. R. Gebman, The Rand Corporation.

Table 13

STRUCTURAL WEIGHTS FOR SUBSONIC CRUISE VEHICLES: CONFIGURATION 5[a]

Material Combination	Weight of Structural Component (lb)[b] Fuselage	Wing	Tail	Nacelle	Reference	Total Weight of Structure (lb)[b]	Total Weight Change (lb)[c]
All aluminum							
Conventional aluminum construction (base case)	344	1248	312	81	..	1985	..
All fiberglass							
Chopped S glass/epoxy skins S glass filament/epoxy substructure	292 (0.85)	..	..	69 (0.85)	2 (p. 66)	..	..
S glass filament and E glass fabric/epoxy layup	..	1123 (0.90)	..	..	2 (p. 67)	..	..
Chopped S glass/epoxy molded	..	..	265 (0.85)	..	2 (p. 61)	1749 (0.88)	-236 (-11.9)
Fiberglass - paper honeycomb							
Chopped S glass/epoxy skins S glass filament/epoxy substructure	292 (0.85)	..	..	69 (0.85)	2 (p. 66)	..	..
Paper phenolic honeycomb core, aluminum skins	..	1023 (0.82)	256 (0.82)	..	3 (p. I-55)	1640 (0.83)	-345 (-17.4)
Cast and molded plastics							
Chopped E glass/polyester centrifugally cast tube	440 (1.28)	..	..	..	3 (p. I-27)	..	..
ABS molded plastic with aluminum fittings	..	1697 (1.36)	424 (1.36)	..	3 (p. I-52)	..	..
Aluminum - conventional construction	..	..	..	81 (1.00)	..	2642 (1.33)	657 (33.1)
Paper and foam							
Polyester-impregnated, spiral-wound paper tube	320 (0.93)	..	..	..	3 (p. I-26)	..	..
Polyurethane foam (natural skin) with aluminum spars	..	1010 (0.81)	253 (0.81)	..	3 (p. I-53)	..	..
Aluminum - conventional construction	..	..	..	81 (1.00)	..	1664 (0.84)	-321 (-16.2)
Wood							
Sitka spruce substructure, mahogany plywood skins	302 (0.88)	1123 (0.90)	281 (0.90)	81 (1.00)	2 (pp. 27-28)	1787 (0.90)	-198 (-10.0)
Sail-wing							
Nylon fabric sail-wing, aluminum frames, nylon fuselage and tail coverings	326 (0.95)	624 (0.50)	281 (0.90)	81 (1.00)	2 (p. 19)	1312 (0.66)	-673 (-33.9)
Graphite filament							
Graphite filament/epoxy (maximum utilization), glass filament or fabric/epoxy where applicable	258 (0.75)	749 (0.60)	234 (0.75)	61 (0.75)	4 (pp. 377-382)	1302 (0.66)	-683 (-34.4)
Titanium							
Titanium (maximum utilization), aluminum where applicable	292 (0.85)	1123 (0.90)	281 (0.90)	69 (0.85)	(d)	1765 (0.89)	-220 (-11.1)

[a]Altitude = 75,000 ft; speed = 515 kn; range = 5500 n mi; payload = 700 lb; gross weight = 8000 lb; turbofan engine.

[b]Numbers in parentheses indicate the fraction of the all-aluminum-component weight.

[c]Numbers in parentheses indicate the percentage of the all-aluminum-configuration total weight.

[d]Unpublished work by J. R. Gebman, The Rand Corporation.

Configuration 1, and a turboprop engine in Configuration 2. For maximum endurance, the cruise speed for the reciprocating engine is only 172 kn, compared to 273 kn for the turboprop. The lower speed requires a wing area much greater than that for the turboprop vehicle, resulting in a significantly greater airframe weight. The weight of the fuel required is correspondingly increased--by about 59 percent. Also, the reciprocating engine is more than twice as heavy as the turboprop. The net effect is a 72 percent increase in gross vehicle weight--and a 182 percent increase in airframe structural weight. That is, the structural weight fraction jumps from less than 0.18 for the turboprop vehicle to more than 0.29 for the reciprocating-engine vehicle.

Thus, Configuration 1 is an example of the detrimental effect of taxing the operating capability of a particular vehicle (in this case, by requiring a reciprocating engine to operate at a high cruise altitude). Obviously, the reductions in structural weight obtained by the materials substitutions indicated in Table 3 are much more significant in this case, where the structural weight fraction is large, than in Configuration 2, where it is relatively small.

The results presented in Tables 9 through 13 can be summarized in terms of a set of weight reduction factors that operate on the fuselage, wing, tail, and nacelle weights obtained for all-aluminum construction. These factors are given in Table 14 for each material combination. One can design a vehicle and determine the weights of the various structural components when made from aluminum, and then estimate the weight savings* with different materials by applying these factors.

The weight saved by materials substitutions can be used to increase the fuel capacity, thus increasing endurance or range. This effect can be illustrated by considering the use of graphite-filament materials in Configurations 4 and 5. Curves of payload versus range for aluminum drones of this type, i.e., Mach 0.9 turbofans at 75,000 ft, are presented in Fig. 1.[1] The substitution of graphite-filament materials results in a weight saving of 215 lb for the 3000-lb all-aluminum

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*Or weight addition, in the case of the cast and molded plastics.

Table 14

WEIGHT REDUCTION FACTORS FOR VARIOUS MATERIAL COMBINATIONS FOR SUBSONIC DRONES

Material Combination	Structural Component			
	Fuselage	Wing	Tail[a]	Nacelle[b]
All fiberglass	0.85	0.90	0.85	0.85
Fiberglass - paper honeycomb	0.85	0.82	0.82	0.85
Cast and molded plastics	1.28	1.36	1.36	1.00
Paper and foam	0.93	0.81	0.81	1.00
Wood	0.88	0.90	0.90	1.00
Sail-wing design[c]	0.95	0.50	0.90	1.00
Graphite filament	0.75	0.60	0.75	0.75
Titanium	0.85	0.90	0.90	0.85

[a]Tail weight is assumed to be 25 percent of the wing weight for the all-aluminum configuration.

[b]Nacelle weight is assumed to be 7.5 percent of the engine weight.

[c]Not applicable for high-speed, low-altitude drones.

drone and 683 lb for the 8000-lb all-aluminum drone, thereby increasing payload capability. Thus, a 3000-lb drone made from graphite-filament materials, carrying a 700-lb payload, would have a range of about 3500 n mi, about 1000 n mi more than that of a 3000-lb all-aluminum drone. And an 8000-lb graphite-filament-materials drone, with a 700-lb payload, would have a range of about 7300 n mi, about 1800 more than that of the same-weight aluminum drone.

The weight savings can also be used to reduce vehicle size, power plant, and required fuel capacity, all of which are interrelated. This has a multiplier effect on the original structural weight savings. The additional weight reductions obtainable by resizing the vehicle have not been examined here. However, they can be significant and should be included in subsequent, more detailed investigations.

Tables 9 through 14 demonstrate the method used here to estimate potential structural weight savings from materials substitutions. Using the basic materials data presented in Table 1 (along with any additional information on these and other materials of interest) and any design method which is available for estimating structural component weights

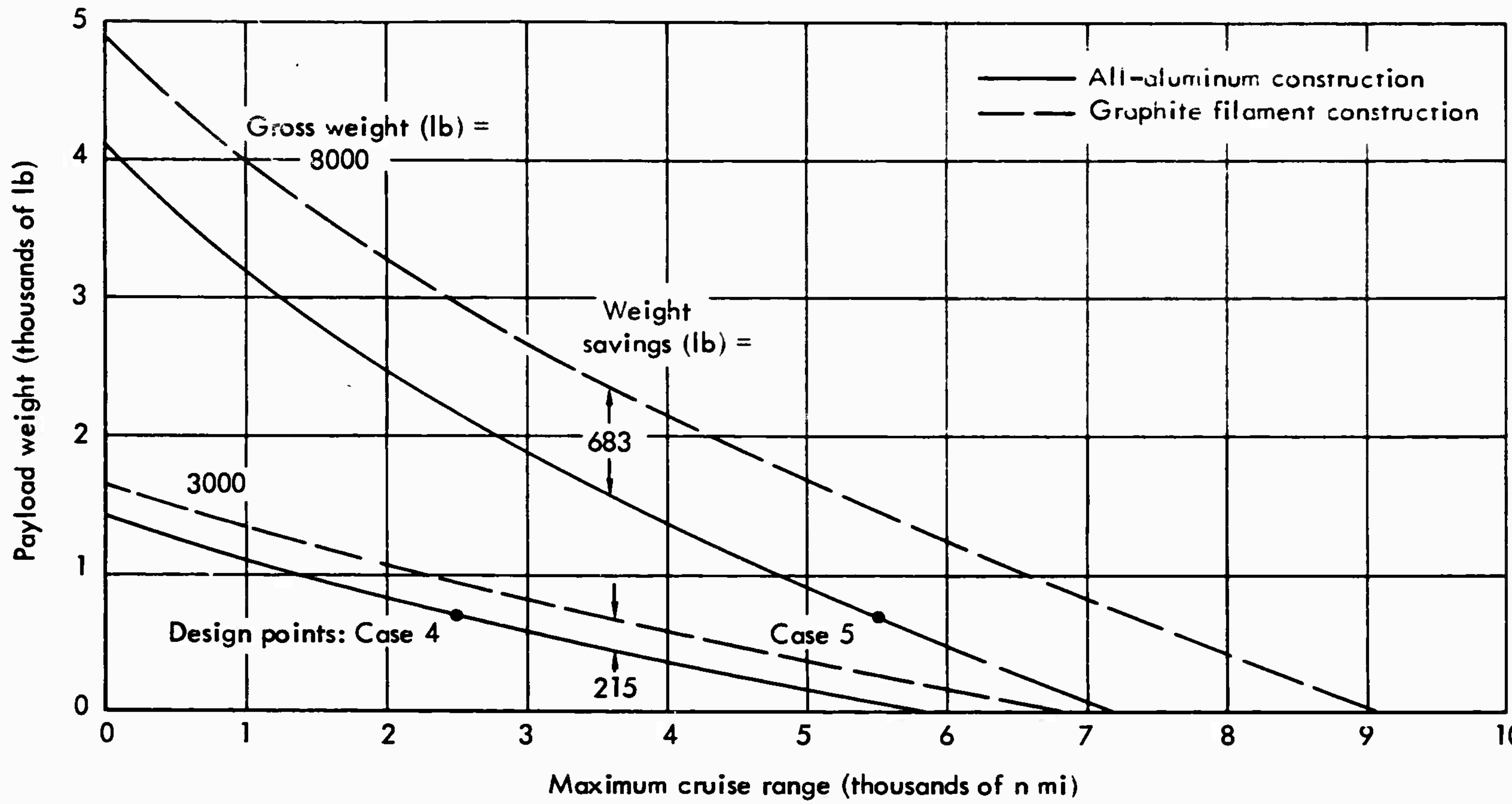

Fig. 1—Effect of substituting graphite filament for aluminum in Mach 0.9 turbofan drone at 75,000-ft altitude for maximum-range cruise missions

for conventional aluminum construction, similar weight estimates can readily be made for any other drone design or combination of structural materials.

SUPERSONIC CRUISE VEHICLES

Considerably fewer structural materials are suitable for use in supersonic-cruise-vehicle airframes than in subsonic vehicles because of the temperatures developed due to aerodynamic heating in supersonic cruise flight. Three specific mission profiles will be considered here to indicate the severity of this aerodynamic heating. The performance and characteristics of drones made from base-case materials are given in Table 15.

Table 15

CHARACTERISTICS OF REPRESENTATIVE SUPERSONIC CRUISE VEHICLES SELECTED FOR ANALYSIS

Configuration	Cruise Speed (Mach No.)	Cruise Altitude (ft)	Cruise Range (n mi)	Gross Weight[a] (lb)	Payload Weight[b] (lb)	Structural Weight[a] (lb)	Engine
6	2.3	75,000	1,150	6,000	700	644	Afterburning turbojet
7	3.0	75,000	950	6,000	700	745	Afterburning turbojet
8	5.0	120,000	1,000	8,000	700	2,117	Ramjet

[a]Constructed from base-case materials: titanium alloys at Mach 2.3, graphite/polyimide at Mach 3.0, and coated columbium alloys at Mach 5.0.

[b]Includes guidance and navigation systems.

The structural material weight-estimating relationships contained in the drone design model developed at Rand are based on a statistical correlation of subsonic drone designs with conventional aluminum airframes. But for the Mach 5.0 configuration, a 50 percent increase in structural weight was assumed, to reflect the lower mechanical properties and higher densities typical of the high-temperature materials required. These assumptions were intended to provide a basis for the analysis of materials possibilities presented here with respect to the actual temperature environments encountered. The base-case materials for this analysis are titanium alloys (Mach 2.3), graphite/polyimide (Mach 3.0), and coated columbium alloys (Mach 5.0).

To obtain an estimate of the operating temperature ranges typical of the three missions being discussed, representative bounding values have been computed utilizing the following expression:

$$T = T_o\left[1 + R\left(\frac{\gamma - 1}{2}\right)M^2\right]$$

where T is either the adiabatic wall temperature, T_a in °R, or the stagnation temperature, T_s in °R; T_o is the ambient air temperature at altitude in °R (T_o is 395°R at 75,000 ft and 435°R at 120,000 ft); M is the local Mach number; R is the Prandtl recovery factor (R = 0.864 when computing T_a and 1.0 when computing T_s); and γ is the ratio of specific heats, a constant equal to 1.4. The value of T_a is assumed to be a representative lower bound, indicating the average temperature over a significant portion of the aerodynamic surface of the vehicle; T_s is taken as an upper bound of the temperature range, representing the local temperature on wing leading-edge surfaces, etc.

The computed values of T_a and T_s (converted to °F) are given in Table 16. The problem of materials selection for each of the three supersonic vehicle airframes will now be individually considered on the basis of these temperature-range estimates.

Mach 2.3 Flight

The mechanical properties of many of the materials that were evaluated for subsonic cruise vehicles (where aerodynamic heating is negligible) are seriously degraded at temperatures of only a few hundred degrees Fahrenheit. These materials include, in particular, the polyester and epoxy plastics which were suggested as matrix materials for the filament-, chopped-fiber-, and fabric-reinforced composite systems. Also included in this group are the unreinforced ABS molded plastic and the polyurethane foam. Obviously, the poly-

Table 16

REPRESENTATIVE AERODYNAMIC HEATING TEMPERATURE RANGES

Configuration	Cruise Speed (Mach No.)	Altitude (ft)	T_a (°F)	T_s (°F)
6	2.3	75,000	295	355
7	3.0	75,000	550	650
8	5.0	120,000	1,850	2,150

ester-impregnated paper, the paper phenolic honeycomb, and the wood materials are also restricted to relatively low-temperature environments.

Thus, of the nine material combinations evaluated for subsonic vehicles, only two can even be considered for a Mach 2.3 vehicle, viz., aluminum and titanium.

In the 295° to 355°F temperature range (estimated for Mach 2.3 flight), a typical aluminum-alloy airframe material such as 2024-T4 retains from 85 to 90 percent of its room-temperature tensile yield strength and 90 to 95 percent of its room-temperature stiffness after 100 hr of exposure.(5) For much longer times at high temperature, however, the strength may drop to as low as 50 percent of the room-temperature value, although the stiffness remains relatively constant. The significant fact is that above 200° to 250°F, the strength properties of aluminum alloys become very sensitive to both temperature and time at temperature.

Configuration 6 was selected to represent a mission near the upper limit of cruising speed at high altitudes for which aluminum alloys can be extensively utilized. The thermal environment is at least as severe at altitudes above and below 75,000 ft due to the higher ambient air temperature at other altitudes.

Since the 644-lb structural weight estimate for this vehicle was established assuming a material having the room-temperature properties of aluminum alloys, the actual weight will be from 10 to 15 percent higher if aluminum alloys are used, to offset the degrading effect of the operating temperature on the strength and stiffness properties.

At room temperature, the typical titanium airframe alloys, e.g., Ti-6Al-4V and Ti-6Al-6V-2Sn, are about 60 percent stiffer than the aluminum alloys, but also about 60 percent heavier. Thus, there is little advantage to be gained by substituting titanium for aluminum for stiffness-critical components. However, the typical strength properties of titanium are at least three times higher than those for aluminum, resulting in a specific strength about twice as high. Therefore, weight savings of 10 to 15 percent are possible, through the substitution of titanium for aluminum (see Table 1). However, the titanium alloys suffer about the same strength and stiffness losses in the 295°F to 355°F temperature range as the aluminum alloys, the Ti-6Al-6V-2Sn alloy having a slightly better strength retention.[5]

Thus, a titanium airframe designed for the 295°F to 355°F temperature environment can be expected to weigh about the same as an aluminum airframe designed for room-temperature conditions. That is, for Configuration 6, an aluminum airframe would weigh about 15 percent more than a 644-lb titanium airframe.

Steel alloys are also candidate materials. An alloy such as Type 301 stainless steel (Fe-18Cr-8Ni) would result in a structural weight comparable to that of titanium.

There is one additional group of materials, represented by the graphite/polyimide composites included in Tables 1 through 7, which have a much higher potential for supersonic-flight environments, however. These are the high-temperature polymer matrix composites, of which the polyimides are currently the best known. Recent work has indicated good strength and stiffness retention of polyimide matrix composites after long exposures at 600°F.[6] These high-temperature polymers were not considered for the subsonic-flight vehicles, since temperature was not a consideration. They are not yet as well-developed as the epoxies and are presently slightly more expensive and difficult to work with.

When used with any of the reinforcements included in Table 1, the polyimides offer composite strength and stiffness properties at least as high as those of the epoxies. And the densities are about the same. Hence, the weight savings for epoxy matrix composites at room temperature, indicated in Table 1, can be taken as the weight savings for polyimide matrix composites in the 295°F to 355°F temperature environment of Configuration 6. Obviously, these high-temperature polymers have the same high potential for revolutionizing the construction of supersonic vehicles as the room-temperature polymers are presently demonstrating for subsonic vehicles.

Mach 3.0 Flight

In the 550°F to 650°F temperature range that would be encountered by Configuration 7, the aluminum alloys retain only 10 to 30 percent of their room-temperature strength.(5) Thus, they must be eliminated from practical consideration.

The titanium alloys retain about 70 to 75 percent of their room-temperature strength at these temperatures, and about 80 percent of their room-temperature stiffness. Since, as indicated in Table 1 and discussed for Configuration 6, the titanium alloys offer a 10 to 15 percent weight savings (relative to aluminum) for room-temperature applications, a titanium airframe designed for the 550°F to 650°F temperature environment of Configuration 7 can be expected to weigh from 10 to 20 percent more than the 745-lb base-case airframe.

As for Configuration 6, steel alloys such as Type 301 stainless will result in a structural weight very close to that for titanium--slightly higher because of the lower specific strength of the steel alloys.

The polyimide matrix materials, discussed for Configuration 6, were indicated to have good strength and stiffness retention after long exposures at 600°F. Limited data available to date indicate the following strength-retention percentages when the composites were tested at 600°F after 500 hr exposure at 600°F:(6)

E glass-fabric/polyimide--65 percent
S glass-filament/polyimide--40 percent
Graphite-filament/polyimide--75 percent

All three composites have similar densities. The S glass-filament/polyimide composite is about three times as strong as the E glass-fabric polyimide at room temperature and hence is still twice as strong at 600°F, even though it suffers a greater degradation. Likewise, having a higher room-temperature strength than the graphite-filament/polyimide, it has a comparable strength at 600°F. However, the stiffness of the high-modulus graphite-filament-reinforced polyimide composite remains about five times greater than that of the S glass-filament-reinforced polyimide, the stiffness being less sensitive to temperature than the strength.

In summary, the E glass-fabric/polyimide composite is not a likely candidate for primary airframe components at Mach 3.0, being only about one-half as strong and stiff as the S glass-filament/polyimide composite. However, as Table 1 and previous discussion indicated, E glass is less expensive than S glass (although both are relatively low-cost materials), and therefore it may be useful for lightly loaded components such as fairings or access covers.

For strength-critical components, the S glass-filament/polyimide composite offers equal performance and is much less expensive than the graphite-filament/polyimide composite. For stiffness-critical components, the graphite-filament/polyimide material is five times better--but more than four times as expensive. Thus, it is necessary to determine the value of a pound of weight saved. However, if the cost of graphite filaments is greatly reduced during the next few years, as predicted, the graphite-filament-reinforced polyimide will clearly be the better material to use.

As previously pointed out, aluminum is not a practical material for a Mach 3.0 vehicle. Fortunately the graphite-filament/polyimide composites provide adequate strength at Mach 3.0 and result in a vehicle weight about equal to that given in Table 15. Hence, the data of Table 15 for Mach 3.0 flight should be interpreted as applying for vehicles constructed of materials equivalent to graphite-filament/polyimide.

The temperatures developed during Mach 3.0 flight are very nearly the maximum allowable for the polyimides, and Configuration 7 represents a limiting case for this type of material. Other high-temperature polymers are currently being investigated, however, and while few actual results are presently available, it appears that operating temperatures as high as 1000°F will be attainable.

Mach 5.0 Flight

The 1850°F to 2150°F thermal environment associated with Configuration 8 automatically eliminates the aluminum alloys and the high-temperature polymer matrix composites from consideration, because of their temperature limits (defined in the discussion of Configuration 7).

The titanium alloys and the stainless steels both lose strength and stiffness very rapidly above 800°F and are also eliminated from consideration for the temperature environments of Mach 5.0 flight. Beryllium alloys and iron-chromium-nickel-base alloys are inadequate above about 800°F and 1200°F, respectively.

Nickel is the base element for most of the heat-resistant superalloys that even approach the temperature range of Mach 5.0 flight. These materials, of which Hastelloy X and René 41 are well-known examples, are typically limited to applications in the 1200°F to 1500°F range. The cobalt-base alloys are only slightly more heat-resistant, extending the upper limit to about 1800°F.

However, one particular nickel-base material consisting of thoria dispersed in a nickel matrix (commonly referred to as TD nickel) does have good stability at 1850°F to 2150°F, although its mechanical properties are poor. For example, its room-temperature yield strength and stiffness are about 55,000 psi and 17 x 10^6 psi, respectively;[7] at 2000°F they drop to about 15,000 psi and 8 x 10^6 psi, respectively.[7] The yield strength of TD nickel at 2000°F is about 40 percent that of an aluminum alloy at room temperature; the stiffness is about 75 percent that of an aluminum alloy at room temperature. Also, the density of TD nickel is about 3.2 times that of an aluminum alloy.

Thus, the 2117-lb structural-weight estimate for the base case (which is 50 percent higher than would be predicted if an aluminum alloy operating at room temperature were assumed) would have to be multiplied by an additional factor of about 4 if TD nickel were used for Configuration 8. Obviously TD nickel is not a practical material for this vehicle.

The columbium alloys are more suitable materials than TD nickel for Configuration 8. To avoid surface embrittlement and scaling at high temperatures, the columbium alloys are almost always used with a protective coating--hence, the designation, "coated columbium." A wide range of columbium alloys are available. A typical high-strength alloy such as Cb-15W-5Mo-1Zr has a yield strength of about 50,000 psi at 2000°F, and a stiffness of about 18 x 10^6 psi.(7) This yield strength is about 40 percent higher than that of an aluminum alloy at room temperature; the stiffness is about 70 percent higher. The density of the columbium alloy is only slightly higher than that of TD nickel.

Thus, the 2117-lb structural-weight estimate for the base case could be considered as generally representative of an airframe utilizing a columbium alloy extensively.

The molybdenum alloys such as Mo-0.5Ti are somewhat comparable to the columbium alloys, being about 60 percent stiffer at 2000°F (29 x 10^6 psi), but having a 20 percent lower yield strength (about 40,000 psi) and a 10 percent higher density.(7) The net effect of using a molybdenum alloy for Configuration 8 would also be an airframe weight in the general range of the 2117-lb estimate--perhaps slightly less because of the better stiffness properties of molybdenum alloys. Because the stiffness of these alloys at 2000°F is unusually high, a detailed component-by-component comparative evaluation would be required to obtain a more accurate weight estimate.

Summary

The comparisons of materials for the three supersonic-cruise-vehicle configurations are summarized in Table 17. Finished-part cost ratios similar to those given in Table 1 are also presented.

Reductions in structural weight relative to the base cases can be achieved at Mach 2.3 (roughly 15 to 25 percent) by using S glass/polyimide composites and graphite/polyimide composites and at Mach 5.0 (roughly 10 percent) by using coated molybdenum alloy. There was no material that gave improvement at Mach 3.0 over the base case (utilizing graphite/polyimide) among the materials investigated.

Table 17

RELATIVE STRUCTURAL WEIGHTS AND FINISHED-PART COSTS
FOR SUPERSONIC CRUISE VEHICLES

Structural Material Type	Total Structural Weight Change Relative to Base Material[c] (percent) — Configuration 6 (Mach 2.3)	7 (Mach 3.0)	8 (Mach 5.0)	Ratio of Finished-Part Cost to Aluminum-Part Cost
Aluminum alloys (2024-T4)	15	(a)	(a)	1.0
Titanium alloys (Ti-6Al-6V-2Sn)	(b)	15	(a)	2.2
Steel alloys (301 stainless)	5	20	(a)	1.1
S glass/polyimide composites	-15	60	(a)	1.2
Graphite/polyimide composites	-25	(b)	(a)	2.1
Coated columbium alloys (Cb-15W-5Mo-1Zr)	25	45	(b)	2.6
Molybdenum alloys (Mo-0.5Ti)	10	20	-10	2.5
Thoria dispersed nickel (2 percent thoria)	100	160	(a)	1.8

[a] Not applicable.

[b] Base-case material.

[c] A negative value represents a reduction in weight.

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